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Analysis of reports of ice accretion on aircraft

by

R.F. Jones

(Meteorological Office)

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

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1. Introduction

During the past four years some 800 reports of icing encounters by R.A.F. and civil aircraft have been received in the Meteorological Office and have been analysed for this report. Because no reliable icing intensity meter existed suitable for fitting to operational aircraft the reports of icing severity are necessarily of a qualitative and subjective nature, although in some reports the pilot has estimated the rate of build up of ice on parts of the aircraft within his sight, e.g., windscreen, leading edge, propeller boss. As data from which useful statistical relationships can be obtained the observations are clearly of no value since we have no means of knowing the frequencies with which various levels (temperature or height) were traversed nor the frequency of clouds at those levels. Nevertheless some useful information on the occurrence of icing in various cloud types at different temperatures can be extracted. The great majority of the reports refer to conditions over the British Isles and any deductions made should only be regarded as referring to that area.

2. Qualitative reports of icing severity

(a) Reliability

Three categories of icing severity were used - "low", "moderate" and "high" - but because there was no yardstick by which to assess icing severity the reports were highly subjective, depending on the pilot's experience and probably the amount of trouble caused to him by the icing. In general terms one would expect the rate of build-up of ice on a part of the aircraft visible to the pilot to have been the principal factor in the assessment, but even this is not easy to assess and there would be a natural tendency to assess icing severity from the total build-up of ice over the variable period throughout which the aircraft was subject to icing. The rate of accumulation of ice is, of course, also a function of aircraft speed so that "light" icing to a slow aircraft might be "moderate" or "severe" to a fast aircraft.

The reliance to be placed on the pilot's estimates of severity can be checked, for there were 337 occasions when as well as making a qualitative assessment of icing rate the pilot estimated the accumulation of ice on the aircraft in terms of inches of ice and the time over which the icing occurred. Table I shows the distribution of icing rates so determined with the pilots' qualitative assessments.

Thus, if we defined a "high" icing rate as one leading to an accumulation of ice on the aircraft at 10 in./hr or more, 25 per cent of "moderate" reports and even 14 per cent of "low" reports should really be re-graded as "high" while 34 per cent of the "high" reports would require re-grading as "moderate" or "low".

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The subjective element in the qualitative reports is, therefore, very marked and this requires to be borne in mind in the subsequent discussion.

(b) Distribution with cloud type

The percentage distribution of reports of "high", "moderate" and "low" icing rates within each cloud type is shown in Table II.

It is immediately obvious from Table II, in accordance with general expectations, that the type of cloud in which icing is most likely to be regarded as severe is the cumulus or cumulonimbus type. There is nevertheless a significant percentage of "high" icing rates associated with layer types of cloud which, because of their greater horizontal extent, may constitute a greater total icing hazard than the convection type, and there has been at least one report of "high" icing rate in every cloud type.

(c) Distribution with temperature

On many of the occasions when icing was reported it was possible to determine the ambient temperature by making corrections to the indicated readings of the aircraft thermometer or by estimation from appropriate radiosonde ascents. Temperatures determined in this way may not be more accurate than about $\pm 2°C$ but the distribution of icing experiences with these temperatures will give a useful indication of the temperature zones within which the various icing severities may occur.

The distribution of icing severities in the three qualitative groups "low", "moderate" and "high" with temperature and cloud type is shown in Table III.

It will be seen that, taking all the reports together, there is no significant difference in the distribution with temperature of "low", "moderate" and "high" icing rates. In many types the frequencies may reflect no more than the relative frequencies with which cloud of that type occurred at the temperature shown, e.g., 9.5 per cent of all reports of "low" icing rates experienced in Sc cloud occurred at temperatures between from -11°C to -15°C (Table III). This may be because 9.5 per cent of all flights in Sc cloud at temperatures below 0°C were in the temperature band from -11°C to -15°C or because there is a decreased risk of icing in the temperature band -11°C to -15°C. Without knowing how often an aircraft flew in Sc cloud in this temperature band without experiencing icing it is impossible to separate the two effects. "Nil" reports were asked for on the same form as used for icing reports but it is very unlikely that "Nil" reports received the same attention as positive reports - a total of 74 Nil reports was received compared with 786 icing reports. These are discussed in Section 8 below and it will be seen that there was only one reported occasion of horizontal flight in Sc which gave no icing, at a temperature of -7°C.

3. "Quantitative" reports

On a number of reports an estimate was given of the rate of accumulation of ice on portions of the aircraft visible to the pilot. These reports give more information than the purely qualitative reports dealt with in the previous section but although referred to as "quantitative" reports it is clear that they must be subject to very considerable errors, particularly when the accumulation, as in convection type clouds, occurs over a very short period. However, since there is as yet no suitable instrument for operational aircraft to measure rate of ice accumulation accurately an attempt is made in this section to use this additional information while bearing in mind the large errors to which it may be subject.

If an aircraft is travelling at speed v cm/sec through a cloud of super-

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cooled water content w g/m^3 the rate of accumulation of ice, d, in terms of the thickness of ice deposited on an exposed part of the aircraft, will depend on the efficiency of catch (E) of the supercooled droplets by this part of the aircraft, and the density of the ice deposited, ρ g/cm^3.

The rate of accumulation of ice would be given by:

$$d = \frac{E.v.w}{10^6 \rho} \cdot 3600 \text{ cm/hr} \qquad (1)$$

In the aircraft reports the indicated airspeed is reported in knots and can be converted into true air speed V kt while d is reported by the pilot in inches.

$$V = \frac{v}{51.5} \quad (1 \text{ kt} = 51.5 \text{ cm/sec})$$

$$\text{and so } d = 7.3 \times 10^{-2} \frac{E.V.w}{\rho} \text{ in./hr from (1)}$$

We can then obtain the water content of the air provided we know or can estimate ρ/E since

$$w = 13.7 \frac{d}{V} \cdot \frac{\rho}{E} \text{ g/m}^3 \quad (d \text{ in inches, V in kt}) \qquad (2)$$

E will depend on the shape of the collecting surface, the drop-size distribution of the droplets and the speed of the aircraft while ρ will also depend on the drop-size distribution and the temperature. If the drops are large and the temperature not greatly below 0°C the drops will tend to flow on the surface before freezing completely, leading to a deposit of clear ice of high density. If, however, the drops are small or the temperature is very low the drops will freeze on impact, leading to the formation of rime which, because of the air trapped between the frozen droplets, will have a low density. A part of the aircraft with a large radius of curvature will so deform the airflow past it that, although a high proportion of the large drops having sufficient momentum to overcome the deformation of the air track will impinge on the surface, only a small proportion of the smaller drops will be caught. On the other hand a part having a small radius of curvature will deform the airflow so little that a very much higher proportion of all the drops will be caught. Once ice has begun to form, the shape of the collecting surface will be modified and the efficiency of catch, E, will change accordingly. Thus, even if we know E initially for a particular part of the aircraft we would expect E to increase as ice accumulated since the effect of ice accumulation would usually lead to a reduced radius of curvature of the collecting surface.

On most of the flights reported here the ice formation was reported as being on the leading edge of the wing of the aircraft. If we assume a radius of curvature of the leading edge of 15 cm and a true airspeed of 200 mph then the efficiency of catch of the leading edge (ref. 1) is about 0.1 to 0.2 for drops of 10 μ radius, about 0.4 for drops of 20 μ radius and about 0.6 for drops of 30 μ radius. The mean droplet radius measured in clouds of all types in the United States (ref. 2) ranges between 5 μ and 10 μ and only a small proportion of droplets measured exceeded 15 μ in radius. It seems likely, therefore, that the efficiency of catch of the leading edge of most aircraft is likely to be of the order of 0.2 in most clouds but the efficiency will rise considerably when the droplet size is large as in freezing drizzle or rain. In such circumstances the type of ice formation is likely to be clear ice. The density of rime ice which forms on an aircraft is not known with any accuracy but may be about 0.1 to 0.2 g/cm^3 while the density of clear ice is probably about 0.8 to 0.9 g/cm^3. We see, therefore, that the ratio ρ/E

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in equation (2) may be about unity for both rime ice and clear ice and as a rough approximation we may re-write equation (2) in the form

$$w = 13.7 \frac{d}{V} \text{ g/m}^3 \qquad (3)$$

At low temperatures when even quite large drops may be expected to give rapid formation of rime ice equation (3) may considerably over-estimate the value of w while at temperatures close to the freezing point in clouds of high water content with normal mean droplet radius, giving clear ice formation, w may be under-estimated. Variations in w, however, caused by the departure of ρ/E from unity may be no greater than those caused by the large errors inherent in the method of estimating rate of ice formation. For example, a typical statement from a pilot that $\frac{1}{4}$ in. of ice formed in one minute (d = 15) cannot reasonably be expected to be better than $\frac{1}{8}$ to $\frac{3}{8}$ inch in 1 - 2 min. which gives values of d varying between 3.75 and 22.5 with corresponding variability in w from equation (3).

With these inadequacies of the data in mind the "quantitative" icing reports have been analysed using equation (3) to give rough values of w. 235 reports were available for analysis in this way.

4. Type of icing

Three main types of icing were generally reported by the pilot, namely "clear", "rime" and "mixed". Included in "mixed" were reports of "cloudy" ice and two reports of packed snow.

The distribution of these types of icing with w is shown in Table IV while the distribution with temperature is shown in Table V. The three main types of icing are dealt with in detail in Sections 5, 6 and 7 below.

5. Clear ice formation

(a) Water content and temperature of formation

It will be seen from Table IV that there is a maximum frequency of occurrence of water content leading to clear ice formation in the range 0.21 to 0.30 g/m^3 which is a reasonable value for the water content of many icing clouds (ref. 2) and suggests that the method used may give reasonable estimates of water content. The method, however, leads also to an apparently surprisingly large number of high water contents (22 in excess of 1 g/m^3 with a maximum value of 5.48 g/m^3) and the question arises as to how accurate these derived values may be. Assessments of water content by the rotating cylinder method have led to the conclusion that water contents of this order are very infrequent, if they exist at all, but further examination (ref. 3) has shown that this method becomes unreliable when water contents are high especially when the temperature is also relatively high. At temperatures above about -15°C the method used was unlikely to be effective at water contents greater than 1 - 2 g/m^3. As Table V shows, all but three of the clear ice occasions occurred at temperatures above -15°C so that for similar reasons derived water contents in excess of 1 - 2 g/m^3 are unlikely to be accurate.

As indicated in Section 3 above the water contents w associated with clear ice are unlikely to be over-estimated because of the value of unity ascribed to ρ/E in equation (2) and, since the true airspeed of the aircraft (V) is known with reasonable accuracy, the only significant source of error in the values of water content in Table IV for clear ice, leading to an over-estimation, would be in the pilot's estimate of rate of accretion d. The accuracy of the pilot's estimation is impossible

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to assess but most of these occasions called for special comment and were undoubtedly noteworthy in the pilot's experience. On one occasion ($\underline{w}$ = 1.12) the aircraft was struck by lightning and on another ($\underline{w}$ = 1.26), although the aircraft was only in cloud for eight minutes, part of the propeller broke off. In addition on three occasions ($\underline{w}$ = 1.37, 1.14, 2.29) the observations were made over the Atlantic by trained observers of the Meteorological Reconnaissance Flight, while three occasions ($\underline{w}$ = 2.14, 2.74, 3.00) were separate reports from three aircraft flying in the same cloud mass. There seems reason, therefore, to believe that the true water contents in excess of 1 g/m^3 occurred although the derived values of water contents greater than 2 g/m^3 are probably not reliable. Table V, however, suggests that these water contents are very unlikely at temperatures below -15°C and this is more clearly brought out in Table VI where the occurrences of different water contents with temperature are tabulated for clear ice occasions only. There is, however, a definite risk of severe clear ice formation in suitable clouds at any temperature between 0°C and -15°C.

(b) Cloud type

Having established by the analysis of Section 5(a) above that clear ice formation is very unlikely with any appreciable severity at temperatures lower than -15°C it is of interest to see whether the range of conditions under which clear ice formation can occur can be further narrowed. The 84 occasions of clear ice formation have, therefore, been analysed with respect to cloud type with the results shown in Tables VII and VIII.

It is clear that little narrowing of the range of conditions can be achieved from these tables since conditions favourable for clear ice formation can occur, even leading to severe accumulation, in all the types of cloud which may be expected at temperatures higher than -15°C. The only slight gain is that the three occasions of clear ice formation in precipitation below cloud all occurred at temperatures higher than -5°C (two at a temperature of -1°C). It is perhaps surprising to find so many occasions in thick layer cloud, some of great severity, since in this type of cloud normally associated with widespread precipitation it had been anticipated that at temperatures below 0°C little supercooled water would be present once precipitation had commenced. Nevertheless precipitation was reported on 20 of the 26 occasions of icing in St, Ns, As. Eight of these 26 occasions were reports from Meteorological Reconnaissance aircraft where, since a trained observer was carried, the accuracy of reports should be high. It is noteworthy that these eight occasions gave derived cloud water contents between 0.23 and 0.69 g/m^3 and five of these were in precipitation, although in three the precipitation was reported as drizzle. Two high derived values (2.77, 3.03 g/m^3) occurred in conditions when orographic uplift may have been expected to lead to higher water contents in the cloud; in one case the aircraft had been in cloud for three hours with only light rime icing and only encountered heavy clear ice over the Cheviot Hills. A similar occasion occurred, however, in mid-Channel (derived water content 2.14 g/m^3) when with no apparent change in cloud appearance there was a sudden onset of clear ice formation after three hours in cloud with rime icing. In this case as in the other two cases the aircraft was in frontal precipitation and it appears therefore that frontal cloud may on occasions contain limited volumes of high water concentration, possibly associated with embedded convection cells. These cells may be initiated by forced uplift over high ground or by other less obvious effects. A noteworthy occasion, when the trigger effect may have been convergence in a trough of low pressure associated with a depression over North France, occurred on 1st January, 1953. On this occasion 23 reports of icing on aircraft were received - the majority of them reported severe icing - and an analysis of three of these occasions gave derived values of water content - included in the tables above - of 2.14, 2.74 and 3.00 g/m^3. Cloud tops were about 10,000 ft and the cloud

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base temperature about 1°C at 1,200 ft. The icing was experienced at heights between 2,500 and 3,000 ft and no precipitation was reported. The type of icing reported, "clear with rough or nobbly surface", suggested the presence of large drops. Ascent of air from cloud base to about 4,000 ft would only make available about 1 g/m^3 of free water so that if the derived water contents are true it seems likely that the water content at 2,500 - 3,000 ft had been reinforced by the descent of water to these levels from higher in the cloud. With a cloud top temperature in the region of -15°C it seems possible that the absence of precipitation could be ascribed to a deficiency of ice crystals in the cloud with consequent growth of large cloud particles by coalescence in the liquid phase. The large droplets, approaching drizzle drop size, with a rate of fall in still air of 1 - 2 m/sec, may then have fallen from above into the layer between 2,500 and 3,000 ft, where the temperature was still 1 - 2°C below freezing. Intermittent slight drizzle was reported at the ground in the neighbourhood of these reports.

(c) Distances over which clear ice formation occurred

From a knowledge of the time over which clear icing was experienced and the true air speed of the aircraft it is possible to determine the distances over which the various derived water contents were experienced for the 84 clear ice occasions. The distribution is shown in Fig. 1. In interpreting this figure it must be borne in mind that a pilot will not willingly suffer severe icing without taking remedial measures, e.g., change of course or change of altitude or use of de-icers when fitted. Thus, although Fig. 1 suggests that high water contents only occur over horizontal distances less than 20 nautical miles, this straightforward interpretation may not always be true. It is, of course, possible that the volumes of cloud in which the supercooled water content is high are always of limited horizontal extent and some of the reports suggest this. It is clearly true of convection clouds and it may be that something akin to a convection cell existed in all clouds (see Section 5(b) above) in which high water contents were found but on present information it is unsafe to draw this conclusion. Of the 22 occasions when derived water contents were greater than 1 g/m^3 the aircraft on 15 occasions was in cloud for at least seven minutes longer than the period for which the high rate of icing was reported. On eight of these 15 occasions, however, the aircraft changed height; twice being forced down by weight of ice, and on another occasion de-icing equipment was successfully used.

On Fig. 1 are shown two curves, the first of which indicates possible extreme values of water content for various distances, one point only lying outside the curve and the second a more probable curve of extreme values on the assumption that five readings of the 84 over-estimated the water content. This latter curve would suggest that peak values of water content of 5 - 6 g/m^3 may occur over very short distances and that even over a distance of 10 nautical miles water contents of 2 to 3 g/m^3 may be encountered but it must be remembered that derived water contents in excess of 2 g/m^3 are particularly unreliable. For distances in excess of 40 miles, however, it would appear improbable that mean water contents in excess of 0.6 g/m^3 would occur over the British Isles.

6. "Mixed" ice formation

There were 60 occasions when "mixed" ice formation was reported. This type of ice formation may be regarded as occurring in conditions when water concentrations are variable so that on some occasions immediate freezing of the water droplets occurs while for higher water concentrations some flow of water on the surface occurs leading to a mixture of clear and rime ice. "Mixed" ice would also be expected to occur when ice crystals and supercooled water are present simultaneously so that the supercooled droplets act as the cement holding the ice crystals which also impinge on the surface. It is to be expected, therefore, that the density of the deposit on the surface will be

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variable according to the relative concentrations of clear and rime ice and deduced water contents will accordingly be subject to wider errors than for the clear ice occasions.

(a) Water content and temperature of formation

The distribution of derived water contents with temperature is shown in Table IX. This table has many points of similarity with that given for clear ice occasions (Table VI) showing a maximum frequency of water contents in the range 0.21 to 0.30 g/m^3 but with a large number in excess of 1 g/m^3. The distribution with temperature shows a shift of maximum frequency to the -6 to -10°C band and there are few occasions at temperatures lower than -15°C. Two occasions of derived water content greater than 1 g/m^3 occurred, however, at temperatures below -25°C. Both of these were in thick frontal cloud over Scotland and it is possible that the deposits were mainly of rime of low density. Both aircraft were high-speed aircraft for which the efficiency of catch of the droplets would be high so that the factor P/E in equation (2) may well have been considerably less than unity on these occasions leading to a considerable over-estimate of the derived water content.

The maximum derived water content was 20.56 g/m^3. This was experienced on a Dove aircraft in cumulus cloud at 7,000 ft, temperature -8°C, and was described as one inch of a mixture of rime and clear ice, the whole semi-transparent, forming in $\frac{1}{4}$ min. The time interval is so short that the derived water content, apart from consideration of the density of the deposit, cannot be considered reliable.

The remaining six reports when derived water contents were greater than 3 g/m^3 all resulted in special comments by the crew and two of the reports are given here in detail.

(i) Derived water content 4.57 g/m^3 in Ns cloud over Lincoln. Two inches of white rough ice were reported forming in two minutes on all windows round the cockpit, aerials, and also on mainplanes despite de-icing fluid. "There was only slight rime on climb up to 14,000 ft then high icing began when rain began. Unable to see out without opening windows since ice covered side windows as well as windscreen. Engine boost fell off due to ice on air intakes, though using hot air. Had to abandon details and return. De-icing fluid caused ice to break away from mainplanes in irregular patches. Disturbed airflow caused loud moaning sound clearly audible inside cabin". An advancing warm front was about 100 miles away to the SSW. The estimated temperature at 14,000 ft was -12°C but the precipitation was described as sleety rain.

(ii) Derived water content 3.42 g/m^3 in Cu, 40 miles north of Glasgow. Three inches of opaque hard ice were reported to have formed in five minutes on the propeller domes and leading edges of a Pionair aircraft. "Light icing was experienced at 7,000 ft, temperature -9°C, followed by a sudden heavy accretion. Indicated airspeed fell from 130 to 95 kt in level flight ..... There was no turbulence and little tendency for sheets of ice to form on the windscreen or on the wings apart from the leading edge". There was an unstable N-NE airstream over the Highlands leading to 8/8 Cu type cloud. A little light drizzle occurred prior to icing.

Such reports suggest that on these occasions at least the water contents were exceptionally high and may well have been greater than 2 g/m^3.

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(b) Cloud type

Tables X and XI show respectively the distribution of derived water contents with cloud type and the temperature at which icing occurred with cloud type.

As in the cases of clear ice formation the large number of reports of icing in frontal cloud (St, Ns, As, Cs) is noteworthy; it includes a number of severe occasions.

The temperature distribution is also interesting in showing a greater likelihood of icing in frontal cloud at very low temperatures (below -20°C) than in convection cloud. This may be because of the greater frequency and horizontal extent of frontal cloud at these temperatures and the reluctance of pilots to enter well developed convection cloud when they have a good opportunity of observing it sufficiently far ahead to make a detour. At heights corresponding to temperatures below -20°C cumulus tops would be expected to be usually clearly defined and visibility unhampered by intervening layer cloud. Tables VIII and XI would appear to suggest that icing is unlikely in convection cloud at temperatures below -20°C but it may be dangerous to draw this conclusion. The presence of supercooled water on some occasions in frontal cloud at temperatures well below -20°C is, however, certainly to be inferred from these tables.

(c) Distances over which "mixed" ice formation occurred

With the same restrictions as discussed under para.5(c) a curve, Fig. II, can be drawn showing the distance over which the various water contents were derived.

The curve indicated for extreme values is very similar to the most probable curve in Fig. I (shown dotted in Fig. II) giving added weight to that curve as an indication of the extreme values of water content likely to be encountered over various distances in cloud.

7. Rime ice formation

There were 88 occasions when rime ice was reported. At temperatures close to the freezing point this type of icing occurs when the droplet size is small and each droplet freezes instantaneously on impact. At low temperatures quite large drops, if present, may also freeze instantaneously. Because of the great variation in density of the deposit combined with the variation of efficiency of catch with droplet size, water contents derived from rime ice occasions may be substantially in error, particularly at low temperatures if large drops are likely to have been present (e.g., in some convection clouds). High values of water content derived from observations at low temperatures must, therefore, be regarded with great reserve.

(a) Derived water content and temperature of formation

The distribution of derived water contents with temperature is shown in Table XII. There is a clear distinction between Table XII and the similar Tables VI and IX for clear and "mixed" ice. In the latter tables there is a marked decrease in frequency of ice reported at temperatures lower than -15°C but in Table XII 27 per cent of all incidents occurred at these low temperatures, the lowest being -34°C (two occasions). This is, of course, in accordance with expectation indicating the presence of supercooled water in cloud but little flow of water after impinging on the aircraft surface at temperatures below -15°C. It is interesting, however, to note that the greatest frequency of reports is in the -1°C to -5°C band, just as it is in the clear ice occasions, indicating presumably that at these temperatures in cloud the free water content may sometimes be predominantly in the form of very small droplets (rime ice)

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and sometimes many larger droplets must be present (clear ice). The high frequency of reports in both conditions, however, may merely be a reflection of the relative frequency with which aircraft encountered cloud in this temperature band rather than an indication of increased risk of icing in this band compared with other temperatures.

Once again there is a significant number of derived water contents greater than 1 g/m^3 although the considerations outlined above cause less reliance to be placed on these values than in the case of clear ice. The maximum derived water content was 23.02 g/m^3 and there was also one value of 9.15 g/m^3. On both occasions, one (23.02 g/m^3) in the top of a large cumulus at a temperature of -19°C accompanied by severe turbulence and the other (9.15 g/m^3) in snow below Ns at a temperature of -6°C, it would be reasonable to assume a high efficiency of catch of water drops or snowflakes accompanied by water drops and hence as explained previously a considerable over-estimation of water content.

The two occasions of high derived water content at a temperature of -34°C (1.14 and 1.37 g/m^3) call for special attention. The first occurred in the As sheet ahead of a warm front and the other in cumulonimbus associated with AcAs near to the centre of a depression. On the first occasion icing occurred on a Meteor 8 aircraft in a narrow height band between 22,000 and 26,000 ft 20 miles north of Leuchars. Cloud base was at 8,000 ft at which height sleet was reported (temperature -7°C) but there was stated to be no precipitation above this height. The fact that the aircraft speed was 360 kt would undoubtedly increase the efficiency of catch of any droplets present leading to some overestimation of water content but there must nevertheless have been appreciable liquid water present in cloud at this temperature. On the second occasion the aircraft speed was also high, 450 kt, and this combined with the reported presence of cumulonimbus (supported by the moderate to severe turbulence encountered) makes it likely that the efficiency of catch of the droplets present was high and the value of 1.37 g/m^3 may well be a considerable over-estimate.

Similar considerations may apply to some, if not all, of the high water contents derived and the observations are perhaps better regarded merely as evidence of the presence of supercooled water in significant amounts than true quantitative evidence.

(b) Cloud type

The distribution of derived water contents with cloud type and icing temperatures with cloud type are shown in Tables XIII and XIV respectively.

High values of derived water content were found in all the types of cloud, frontal cloud, non-frontal layer cloud and convective cloud but there was only one icing occasion (discussed in para.7(a)) in convective cloud at a temperature below -20°C. Once again this probably reflects the ease with which a pilot can avoid convective cloud tops rather than an absence of icing at low temperatures in convective cloud. This is supported by the occurrence reported in Section 7(a) above of a high icing rate at a temperature of -34°C when the cumulonimbus cloud was hidden by a layer of AcAs.

As for the cases of "mixed" and "clear" ice, the inference that liquid water is present in frontal cloud at temperatures lower than -20°C can certainly be made.

(c) Distance over which rime ice formation occurred

Fig. III, analogous to Figs. I and II for clear and "mixed" ice formation, shows the distance over which the various water contents were derived. Because of the greater doubt associated with these derived

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water contents the curve drawn, which excludes 10 of the 88 observations, can only be regarded as giving likely values of extreme water contents leading to rime ice formation over various distances. As is to be expected it lies below the curves for clear and "mixed" ice also shown on Fig. III.

8. Reports of no icing in cloud at temperatures below 0°C

74 reports were received specifically mentioning no ice formation in cloud at temperatures below 0°C. 33 of these reports were received from aircraft of the Meteorological Reconnaissance Squadron operating over the Atlantic.

From consideration of the true airspeed of the aircraft it is apparent that in a number of cases (18) although the air temperature was below 0°C the parts of the aircraft most prone to ice formation were probably at a temperature above 0°C so that noticeable icing of the aircraft would be unlikely. If we also exclude those cases (7) in which the aircraft was in cloud for a period of 2 minutes or less and those for which there is insufficient detail (7), 42 reports remain for consideration. More than half (23) of these remaining reports were made when aircraft were ascending or descending, sometimes at considerable speed, through cloud extensive in the vertical so that the time spent in any layer which might have given ice formation may well have been short. Nevertheless the fact that aircraft could, on occasions, ascend through 25,000 ft or more of frontal cloud without experiencing any noticeable ice formation is of interest, particularly as similar ascents on other occasions have led to considerable ice accumulation. The position becomes even more confusing when it is noted that on a number of occasions the precipitation at temperatures well below freezing point was reported as rain. Thus, after a descent in Ns cloud over the Atlantic from 17,860 ft (temperature -18°C) to cloud base at 7,000 ft (temperature -2°C) it was reported that the aircraft was in continuous slight rain while in cloud but with no icing. Whether the rain in reality only occurred very close to, or even below, cloud base can only be conjectured but it was not uncommon to have reports of drizzle, rain or sleet in these clouds with no icing. It is significant, however, that in nine of the ten occasions of horizontal flight in frontal cloud without icing it was stated that there was no precipitation in cloud and the remaining report, of sleet, referred to only the first part of the flight and may have reflected the conditions on climb to cruising height. On four of these ten occasions there was precipitation at ground level.

The temperatures on nine of the ten flights in frontal cloud ranged from -5°C to -15°C (-28°C on the other) which is also the range within which a large number of icing reports was received (Table III). It would appear, therefore, that on a few occasions at least the frontal cloud above the freezing level in this temperature band must be composed entirely of dry ice crystals but that more often the ice crystals are wet and/or exist in association with large numbers of supercooled water droplets. The deduction (ref. 1) that, because most frontal rain is assumed to originate from the melting of ice crystals or snowflakes, there is little risk of appreciable ice formation above the freezing level except in a narrow layer close to the 0°C level appears to be invalid.

Of the other nine occasions of no icing in horizontal flight, five were in convection cloud at temperatures between -7°C and -44°C, three in altocumulus at temperatures of -5°C, -16°C and -17°C and one in Sc at -7°C. All the convection cloud occurrences were in conditions under which frequent showers were occurring and it seems likely that the flights were through parts of the clouds in the decaying stage in which the cloud particles were either dry ice crystals or soft hail - this was reported on three occasions. Altocumulus and stratocumulus are regarded as predominantly water clouds and lack of icing on these occasions might reflect an unusually small droplet size but on one occasion (Ac, temperature -5°C) the cloud was described as "mammatus" and was very turbulent with precipitation within cloud in the form of snow.

9. Synoptic conditions where high values of cloud water content ($\underline{w} \geqslant 1.0$ g/m^3) were deduced

Table IV indicates that there were 56 occasions when a value of water content greater than 1.0 g/m^3 was deduced, 22 from clear ice occasions, 18 from reports of mixed ice and 16 from reports of rime ice. As indicated previously the clear ice reports are probably the most reliable while the rime ice occasions in particular may have led to a considerable over-estimate of $\underline{w}$.

The synoptic conditions associated with these high values of $\underline{w}$ have been examined and are discussed in paragraphs (a), (b) and (c) below for clear ice, mixed ice and rime ice occasions respectively.

(a) Clear ice occasions

The 22 occasions divide up into 9 occasions of unstable air (4 on the same day), 3 associated with cold fronts, 3 with quasi-stationary fronts, 1 with a warm front, 1 with an occlusion, 3 with the thick cloud to the north and west of a depression centre where the fronts are ill-marked, 1 with anticyclonic Sc and 1 in precipitation below cloud.

These situations, of course, describe almost all the conditions which can lead to extensive cloud formations but some narrowing of the limits can be achieved. Thus of the occasions of unstable air all were associated with situations giving widespread convective activity, presumably because the pilot found it impossible to avoid the cloud as he could do if isolated convection clouds were forming. The type of situation was, therefore, that in which the instability cloud was formed by the passage of cold air over a warmer sea although it may have spread inland (7 occasions) or by orographic lifting of direct polar air over high ground (1 occasion) or by convergence in a polar trough (1 occasion). The one occasion in anticyclonic Sc also occurred over the sea and since the airflow was from NNE the cloud was presumably also of convective origin.

In the warm front and occlusion cases the severe icing occurred within 100 miles of the position of the surface front and there was continuous precipitation at the ground; in one case there was some possibility that orographic uplift had contributed materially to the icing. In the cold front and quasi-stationary front cases the severe icing occurred within 50 miles of the surface position of the front except on one occasion when the distance was 100 miles. There was precipitation on two of the occasions but not on the remaining three.

The three occasions of extensive cloud near to a depression centre were all within about 250 miles of the centre; on one of these occasions, when there was an ENE'ly airstream across the North Sea in November, convection over the sea was probably a contributory factor.

Although orographic lifting may have been a contributory factor on five occasions there were also five occasions when the severe icing was experienced over the open sea.

(b) "Mixed" ice occasions

The 18 occasions may be divided into 8 occasions of unstable air, 5 associated with warm fronts, 1 with a cold front, 1 with an occlusion, 1 with a quasi-stationary front, 1 with anticyclonic Sc and 1 close to the centre of a depression.

Of the 8 occasions of unstable air two were associated with convection over the sea and two with widespread convection cloud over the

/mountains

mountains of Scotland. The remainder would appear to be associated with more isolated convection within 400-500 miles of the centre of a depression.

Of the five warm front occasions all were within 200 miles of the surface position of the front, two within 50 miles. Four of the five fronts were active giving continuous precipitation at the position where icing occurred and quickly moving but the fifth was weak and slow moving without precipitation. In this latter case however it is probable that orographic uplift was an important factor.

In the remaining three frontal cases the aircraft was very close to (certainly within 50 miles of) the surface position of the front, but only the cold front gave general precipitation.

As in the clear ice occasion the icing in anticyclonic Sc occurred over the sea in winter (both in February).

(c) Rime ice occasions

The 16 occasions comprised 3 occasions of unstable air, 3 associated with warm fronts, 2 with quasi-stationary fronts, 2 with occlusions, 5 in the thick cloud close to a depression centre and 1 below cloud.

Two of the unstable air occasions were associated with thunderstorms, one over the Mediterranean and the other in the Middle East, where orographic effects contributed to widespread activity. The third occasion was in the top of a cumulus cloud over the North Sea.

In the frontal cases the icing occurred on five of the occasions (out of seven) 100 miles or less away from the surface position of the front. There was continuous precipitation at the ground on four of these occasions. On the remaining two occasions the icing occurred in the altostratus sheet 160 and 300 miles from the surface position of the front before precipitation had commenced.

Of the five occasions in the thick cloud associated with the centre of a depression three were 100 miles or less from the centre and the remaining two within 250 miles.

The occasion of icing below cloud is of interest. This occurred in snow beneath the Ns sheet of a quickly advancing active warm front and indicates clearly the possibility of co-existence of ice and super-cooled water in warm front precipitation.

10. Forecasting ice formation

The foregoing analysis has made very clear the variable nature of icing experiences in cloud and gives little hope that accurate forecasting of the degree of icing severity can be achieved. On many occasions the volume of cloud containing appreciable supercooled water must be very limited in either horizontal or vertical extent so that chance alone decides how severe the icing experience of a particular aircraft may be.

Nevertheless the analysis does indicate some considerations which should be taken into account in making forecasts and the conclusions of this paper may be summarised in the following forecasting "rules". Severe icing has been arbitrarily defined as that leading to a derived water content $\underline{w}$ greater than 1.0 g/m^3.

(i) At temperatures below -15°C the most likely type of ice formation is rime ice. (Table V).

/(ii)

(ii) Icing of any type is very unlikely at temperatures below -35°C. (Table V).

(iii) Clear and "mixed" ice formation may be severe in all types of cloud at temperatures between -1°C and -15°C inclusive. (Tables VI, VII, IX and X).

(iv) Severe clear and "mixed" ice formations are very unlikely at temperatures below -15°C but heavy rime ice may occur. (Tables VI, IX and XII).

(v) Conditions favourable for severe clear and "mixed" ice formations will probably be of limited horizontal extent - perhaps not more than 30 nautical miles (Figs. I and II).

(vi) Heavy rime ice formation will probably not occur frequently over horizontal distances in excess of about 20 nautical miles (Fig. III).

(vii) Forecasts of no ice formation at temperatures between 0°C and -35°C are unlikely to be successful, although occasions of no ice formation will probably occur, unless consideration is given to the particular aircraft type and speed for which the forecast is given.

(viii) Severe ice formation, usually clear or "mixed", should be forecast in conditions likely to lead to widespread convective activity if the flight is to be made within the temperature limits indicated above and cloud is expected to reach to the flight level.
In particular, instability over the sea and in direct polar air traversing high ground are situations liable to give occurrences of severe icing.

(ix) The possibility of severe icing, usually clear or "mixed", should be indicated within 100 miles of the surface position of a warm front, when the front is active and quickly moving. In particularly active warm fronts the distance may be up to 200 miles and the icing in weak or slow moving warm fronts may be intensified over high ground. Heavy rime ice may be experienced in the altostratus sheet as much as 300 miles ahead of the surface position of the warm front and ahead of the associated rain belt.

(x) Severe icing may occur within 50-100 miles of the surface position of cold fronts, quasi-stationary fronts and occlusions.

(xi) In the thick cloud associated with the centre of a depression where the fronts are poorly defined, particularly to the north and west of the centre, severe icing may occur within 250 miles of the centre. In many areas, of course, these conditions will be covered by those described under (viii) above.

References:

(1) Ice accretion on aircraft. Meteorological Report No. 9. Meteorological Office, 1951, pp.10, 11.

(2) Lewis, W. Meteorological aspects of aircraft icing. Compendium of Meteorology. Boston, 1951, p.1201.

(3) Ludlam, F.H. Quart. J.R.Met.Soc., 77, p.663, 1951.

TABLE I

Pilots' estimate of severity	Percentage no. of occasions when icing rate greater than or equal to value shown (in./hr on observable part of aircraft - usually leading edge of wing)												Total no. of reports
	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	20.0	
Low	100	81	64	50	31	30	27	21	16	15	14	3	105
Moderate	100	96	85	73	55	49	42	33	28	28	25	8	150
High	100	99	98	94	87	84	82	73	67	67	66	41	82

TABLE II

Cloud type	Percentage no. of icing severities in the categories shown			Total no. of reports
	"High"	"Moderate"	"Low"	
Stratocumulus (Sc)	12	44	44	185
Cumulus (Cu) Cumulonimbus (Cb) sometimes with Sc	25	40.5	34.5	182
Nimbostratus (Ns) and Stratus (St)	20	33	47	165
Altostratus (As)	13	30	57	107
Altocumulus (Ac)	7	25	68	71
Altocumulus and Altostratus mixed (AcAs)	19	29	52	31
Layer cloud (As,Ns,St) mixed with Cu	18	45.5	36.5	22
Cirrus (Ci) Cirrostratus (Cs) Cirrocumulus (Cc)	(14)	(43)	(43)	7
Out of cloud	(33)	(0)	(67)	12
All reports	17	36	47	782

/TABLE III

TABLE III

Temperatures at which icing was reported - percentage frequency

Cloud type	Pilots' estimate of severity	Temperature range (°C) ⩾0	-1 to -5	-6 to -10	-11 to -15	-16 to -20	-21 to -25	-26 to -30	-31 to -35	-36 to -40	≤ -41	Total no. of reports
Sc	Low	6.8	55.4	27.0	9.5	1.3	0	0	0	0	0	74
	Moderate	1.5	52.3	29.2	13.9	1.5	1.5	0	0	0	0	65
	High	0	55.5	44.5	0	0	0	0	0	0	0	18
Cu,Cb	Low	11.1	29.6	29.6	16.7	3.7	3.7	1.9	0	0	3.7	54
	Moderate	1.8	40.3	38.6	8.8	7.0	1.8	1.8	0	0	0	57
	High	3.3	30.0	43.3	20.0	3.3	0	0	0	0	0	30
St,Ns	Low	4.2	56.3	21.1	15.5	0	0	2.8	0	0	0	71
	Moderate	7.7	46.1	33.4	12.8	0	0	0	0	0	0	39
	High	0.0	65.2	21.7	8.7	4.3	0	0	0	0	0	23
As	Low	0.0	25.9	37.0	11.1	14.8	9.3	1.9	0	0	0	54
	Moderate	10.0	15.0	30.0	10.0	20.0	15.0	0	0	0	0	20
	High	0.0	0.0	25.0	37.5	12.5	0	12.5	12.5	0	0	8
Ac	Low	0.0	18.2	27.3	25.0	9.1	9.1	11.3	0	0	0	44
	Moderate	7.7	7.7	23.0	38.5	23.0	0	0	0	0	0	13
	High	0.0	40.0	20.0	20.0	20.0	0	0	0	0	0	5
Ac,As	Low	0.0	25.0	0.0	25.0	0.0	37.5	12.5	0	0	0	8
	Moderate	0.0	42.9	14.3	14.3	14.3	0	0	14.3	0	0	7
	High	0.0	0.0	66.7	33.3	0	0	0	0	0	0	3
Layer cloud mixed with Cu	Low	0.0	37.5	12.5	25.0	0.0	25.0	0	0	0	0	8
	Moderate	11.1	44.4	33.3	0.0	11.1	0	0	0	0	0	9
	High	0.0	50.0	50.0	0.0	0.0	0.0	0	0	0	0	2
Ci,Cs,Cc	Low	0.0	0.0	0.0	0.0	0.0	50.0	0	0	0	50.0	2
	Moderate	0.0	0.0	0.0	100.0	0.0	0.0	0	0	0	0	1
	High	0	0	0	0	0	0	0	100.0	0	0	1
Out of cloud	Low	0.0	33.3	33.3	0	0	0	0	0	0	33.3	3
	Moderate	0	0	0	0	0	0	0	0	0	0	0
	High	0	75.0	25.0	0	0	0	0	0	0	0	4
All reports	Low	4.4	39.3	26.7	15.1	4.7	5.3	3.1	0	0	1.2	318
	Moderate	4.3	40.8	31.8	13.3	6.6	2.4	0.5	0.5	0	0	211
	High	1.6	42.5	35.1	13.8	4.3	0.0	1.1	2.1	0	0	94

/TABLE IV

TABLE IV

Type of icing associated with different values of derived water content w (g/m^3)

Type of icing	0 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	0.71 to 0.80	0.81 to 0.90	0.91 to 1.00	1.01 to 2.00	2.01 to 3.00	>3.0	Total
Clear	3	7	20	6	5	8	5	6	2	0	9	8	5	84
Mixed	3	8	12	4	3	5	3	2	2	0	10	1	7	60
Rime	20	12	11	10	5	7	2	2	2	1	11	2	3	88
Not reported	1	0	1	0	0	1	0	0	0	0	0	0	0	3
Total:	27	27	44	20	13	21	10	10	6	1	30	11	15	235

TABLE V

Type of icing associated with different temperatures Temperature (°C)

Type of icing	⩾0	-1 to -5	-6 to -10	-11 to -15	-16 to -20	-21 to -25	-26 to -30	-31 to -35	-36 to -40	<-40	Not reported	Total
Clear	2	37	27	15	2	1	0	0	0	0	0	84
Mixed	1	17	25	10	2	1	2	1	0	1	0	60
Rime	2	27	18	16	13	6	3	2	0	0	1	88
Not reported	1	2	0	0	0	0	0	0	0	0	0	3
Total:	6	83	70	41	17	8	5	3	0	1	1	235

/TABLE VI

TABLE VI

84 occasions of clear ice formation: water content and temperature
w (g/m^3)

Temp. °C	0 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	0.71 to 0.80	0.81 to 0.90	0.91 to 1.00	1.01 to 2.00	2.01 to 3.00	> 3.0	Total
⩾ 0	0	0	1	0	0	0	1	0	0	0	0	0	0	2
-1 to -5	2	4	6	4	2	4	2	2	1	0	4	4	2	37
-6 to -10	1	1	7	2	1	3	2	3	1	0	3	3	0	27
-11 to -15	0	1	4	0	2	1	0	1	0	0	2	1	3	15
-16 to -20	0	1	1	0	0	0	0	0	0	0	0	0	0	2
-21 to -25	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Total:	3	7	20	6	5	8	5	6	2	0	9	8	5	84

TABLE VII

84 occasions of clear ice formation: water content and cloud type
w (g/m^3)

Cloud type	0 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	0.71 to 0.80	0.81 to 0.90	0.91 to 1.00	1.01 to 2.00	2.01 to 3.00	> 3.00	Total
Cu, Cb, Cu and Sc	0	1	6	2	2	1	2	1	2	0	2	2	2	23
Sc	1	0	7	3	1	2	2	3	0	0	5	1	1	26
St, Ns, As	1	2	7	1	2	4	1	1	0	0	1	5	1	26
Ac, AcAs	0	3	0	0	0	1	0	1	0	0	1	0	0	6
Below cloud	1	1	0	0	0	0	0	0	0	0	0	0	1	3
Total:	3	7	20	6	5	8	5	6	2	0	9	8	5	84

/TABLE VIII

TABLE VIII

84 occasions of clear ice formation:
temperature and cloud type

Cloud type	Temperature (°C) ⩾ 0	-1 to -5	-6 to -10	-11 to -15	-16 to -20	-21 to -25	Total
Cu, Cb, Cu and Sc	0	7	9	6	1	0	23
Sc	2	13	8	3	0	0	26
St, Ns, As	0	13	8	3	1	1	26
Ac, AcAs	0	1	2	3	0	0	6
Below cloud	0	3	0	0	0	0	3
Total:	2	37	27	15	2	1	84

TABLE IX

60 occasions of "mixed" ice formation:
derived water content and temperature

Temp °C	w (g/m³) 0 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	0.71 to 0.80	0.81 to 0.90	0.91 to 1.00	1.01 to 2.00	2.01 to 3.00	>3.00	Total
⩾ 0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
-1 to -5	0	3	3	2	0	3	1	0	0	0	4	0	1	17
-6 to -10	2	2	2	2	1	2	2	1	2	0	4	1	4	25
-11 to -15	0	1	5	0	1	0	0	1	0	0	0	0	2	10
-16 to -20	0	0	1	0	1	0	0	0	0	0	0	0	0	2
-21 to -25	1	0	0	0	0	0	0	0	0	0	0	0	0	1
-26 to -30	0	1	0	0	0	0	0	0	0	0	1	0	0	2
-31 to -35	0	0	0	0	0	0	0	0	0	0	1	0	0	1
< -35	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Total:	3	8	12	4	3	5	3	2	2	0	10	1	7	60

/TABLE X

TABLE X

60 occasions of "mixed" ice formation:
derived water content and cloud type
w (g/m^3)

Cloud type	0 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	0.71 to 0.80	0.81 to 0.90	0.91 to 1.00	1.01 to 2.00	2.01 to 3.00	>3.00	Total
Cu,Cb,Cu and Sc	0	2	4	0	3	2	2	0	2	0	3	1	4	23
Sc	1	0	3	2	0	2	1	1	0	0	2	0	0	12
St,Ns,As	2	4	4	2	0	1	0	1	0	0	4	0	3	21
Ac,AcAs	0	2	1	0	0	0	0	0	0	0	0	0	0	3
Cs	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Total:	3	8	12	4	3	5	3	2	2	0	10	1	7	60

TABLE XI

60 occasions of "mixed" ice formation:
temperature and cloud type
Temperature (°C)

Cloud type	0	-1 to -5	-6 to -10	-11 to -15	-16 to -20	-21 to -25	-26 to -30	-31 to -35	< -35	Total
Cu,Cb,Cu and Sc	0	6	14	2	1	0	0	0	0	23
Sc	0	5	5	2	0	0	0	0	0	12
St,Ns,As	1	6	5	4	1	1	2	0	1	21
Ac,AcAs	0	0	1	2	0	0	0	0	0	3
Cs	0	0	0	0	0	0	0	1	0	1
Total:	1	17	25	10	2	1	2	1	1	60

/TABLE XII

TABLE XII

88 occasions of rime ice formation:
derived water content and temperature
w (g/m³)

Temp °C	0 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	0.71 to 0.80	0.81 to 0.90	0.91 to 1.00	1.01 to 2.00	2.01 to 3.00	>3.00	Total
⩾ 0	0	0	0	0	0	0	1	1	0	0	0	0	0	2
-1 to -5	9	3	4	2	1	3	1	0	0	0	2	2	0	27
-6 to -10	2	2	4	3	1	1	0	0	2	0	1	0	2	18
-11 to -15	6	2	2	2	1	2	0	1	0	0	0	0	0	16
-16 to -20	0	4	0	1	2	0	0	0	0	1	4	0	1	13
-21 to -25	2	1	0	2	0	0	0	0	0	0	1	0	0	6
-26 to -30	1	0	1	0	0	1	0	0	0	0	0	0	0	3
-31 to -35	0	0	0	0	0	0	0	0	0	0	2	0	0	2
Not reported	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Total:	20	12	11	10	5	7	2	2	2	1	11	2	3	88

TABLE XIII

88 occasions of rime ice formation:
water content and cloud type
w (g/m³)

Cloud type	0 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	0.71 to 0.80	0.81 to 0.90	0.91 to 1.00	1.01 to 2.00	2.01 to 3.00	>3.00	Total
Cu, Cb, Cu and Sc	1	3	2	1	0	1	0	1	0	1	3	1	2	16
Sc	5	2	3	1	1	2	1	0	0	0	1	1	0	17
St, Ns, As	11	4	5	4	3	1	0	1	1	0	5	0	0	35
Ac, AcAs	3	3	1	4	1	3	0	0	1	0	2	0	0	18
Below cloud	0	0	0	0	0	0	1	0	0	0	0	0	1	2
Total:	20	12	11	10	5	7	2	2	2	1	11	2	3	88

/TABLE XIV

TABLE XIV

88 occasions of rime ice formation:
temperature and cloud type

Cloud type	Temperature (°C) ⩾ 0	-1 to -5	-6 to -10	-11 to -15	-16 to -20	-21 to -25	-26 to -30	-31 to -35	Not reported	Total
Cu, Cb, Cu and Sc	1	3	5	1	4	0	0	1	1	16
Sc	0	13	1	2	1	0	0	0	0	17
St, Ns, As	0	10	6	9	4	4	1	1	0	35
Ac, AcAs	0	1	5	4	4	2	2	0	0	18
Below cloud	1	0	1	0	0	0	0	0	0	2
Total:	2	27	18	16	13	6	3	2	1	88

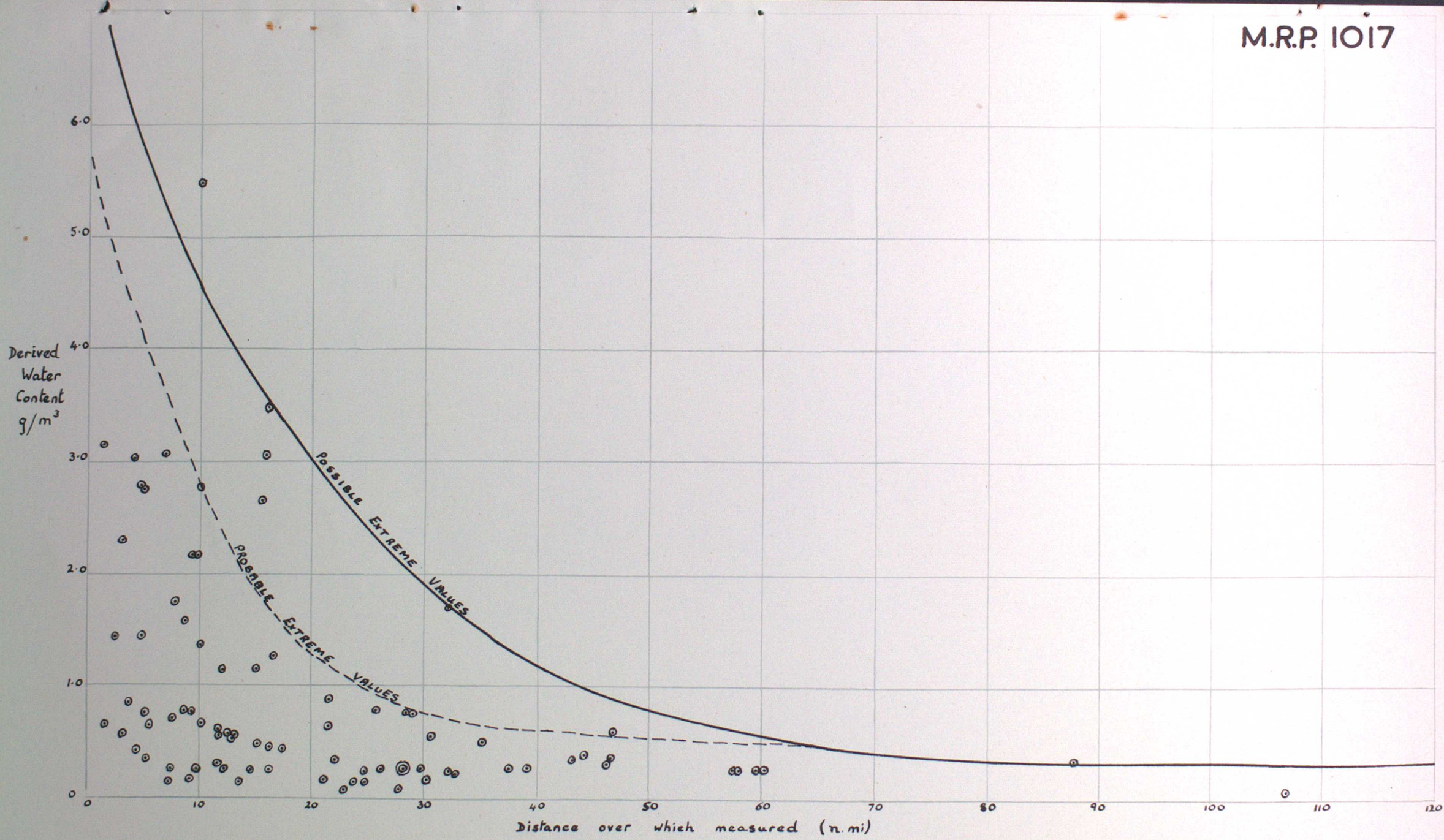

FIG. I Distances over which different values of water content were derived — Clear ice conditions only (84 occasions)

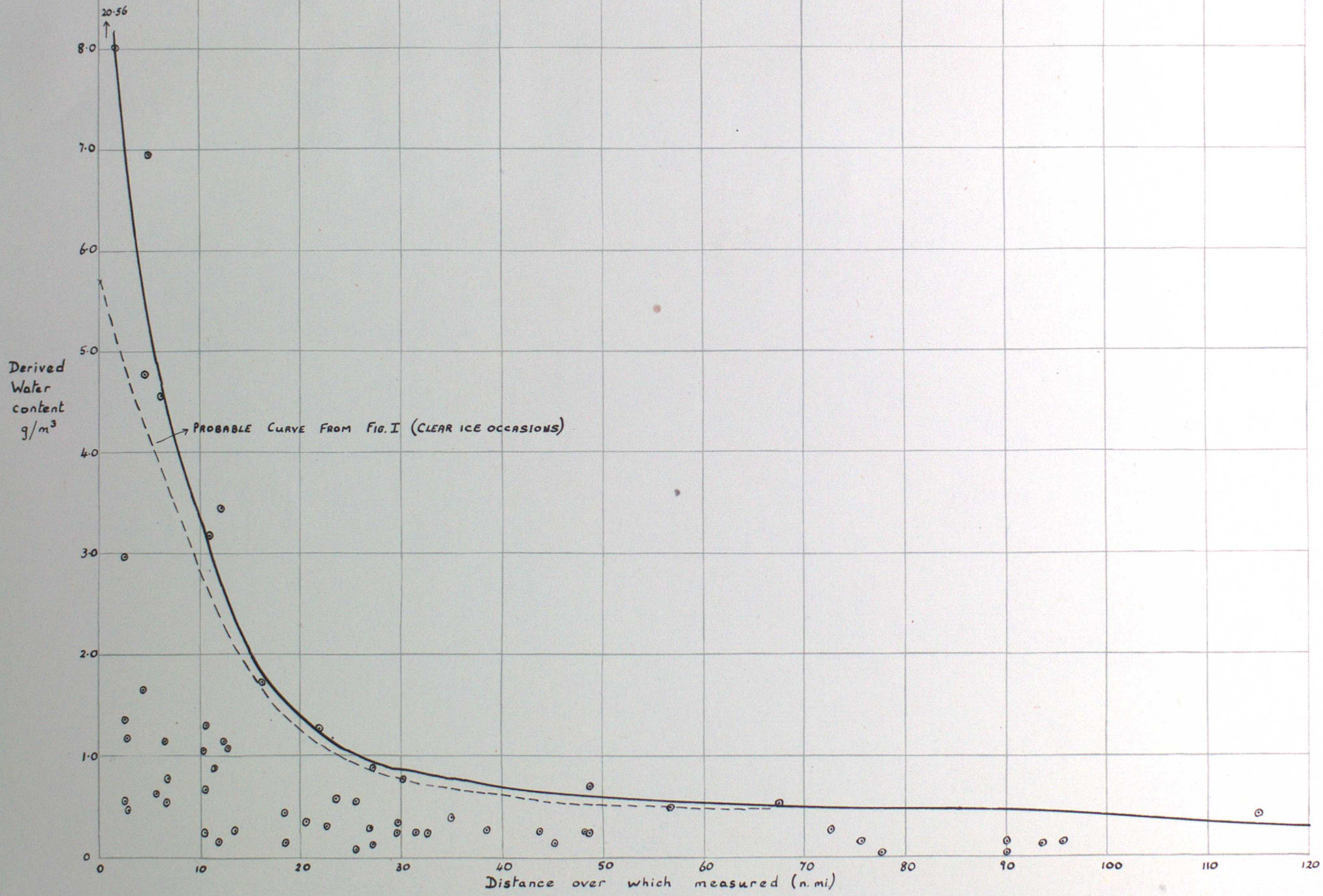

FIG. II Distances over which different values of water content were derived — "Mixed" ice conditions only (60 occasions)

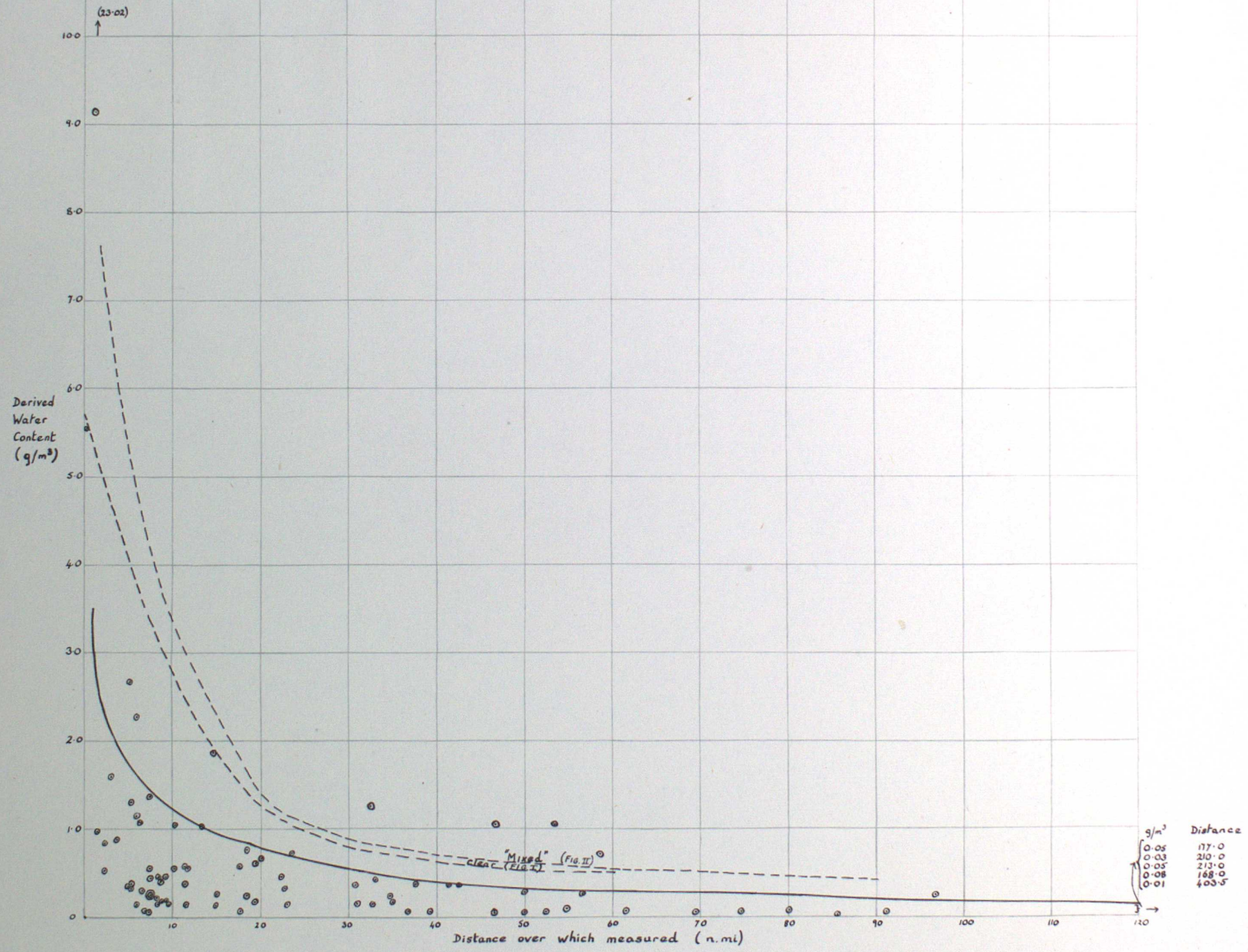

FIG. III Distances over which different values of water content were derived — Rime ice conditions only (88 occasions)